Variations of Geomagnetic Activity with Lunar Phase

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Abstract. An analysis of 31 years of K_p data suggests a variation of geomagnetic disturbance with lunar phase. A general increase in geomagnetic activity of about 4% begins after full moon and lasts for seven days. A general decrease in geomagnetic activity of about 4% is found for the seven days preceding full moon. A study of randomized data indicates that the probability that these variations should have occurred by chance is less than 5%. The effect is found to be associated with the K_p data derived from periods of geomagnetic quiet conditions; it is not evident in the data from disturbed periods.

Introduction. Reports of lunar influence on a number of geophysical variables have appeared in the literature. *Bradley et al.* [1962] and *Adderley and Bowen* [1962] claim to find a lunar influence on rainfall. *Bigg* [1963*a*] presents evidence for a lunar modulation of freezing nucleus concentrations measured in the lower atmosphere. *Bowen* [1963] reports variations in the incoming meteor rate with lunar phase, and *Adderley* [1963] claims a lunar effect on the amount of atmospheric ozone. *Dorman and Shatashvili* [1961] present evidence for a lunar diurnal variation in the intensity of the neutron component of cosmic radiation dependent on lunar phase. Acceptable physical mechanisms for the various lunar modulation effects are not easy to find.

The search for a better understanding of these surprising lunar influences led *Bigg* [1963*b*, *c*] to re-examine the earlier work of *Sucksdorff* [1956] on the influence of the moon on geomagnetic disturbances. Several confusing and contradictory claims have been made in previous lunar-geomagnetic activity studies:

1. That there is a distinct decrease of geomagnetic activity, averaging 12% during new moon, and a less marked decrease of 7% during full moon. Geomagnetic activity is 7% higher than average during first quarter [*Sucksdorff*, 1956].

2. That there is a minimum of geomagnetic disturbance at new moon, 20% lower than any other minimum on the curve, and a broad maximum of geomagnetic activity shortly after full moon [*Bigg*, 1963*b*].

3. That there is a decrease in the frequency of magnetic storms at new moon and a tendency for magnetic storms to occur preferentially near first and third quarters [*Bigg*, 1963*b*].

4. That the decrease in the frequency of magnetic storms at new moon applies only to the gradual-commencement type of storm. The sudden-commencement storms show an increased frequency at new moon [*Bigg*, 1963*c*].

Bartels [1963] shows that the conclusions stated in paragraph 3 are questionable, since randomizing the data yields variations of size comparable to those in the lunar data.

It is the purpose of this paper to determine, by further investigation, whether genuine influences of the moon on geomagnetic activity may be present. It is suggested herein that correlations with lunar phase do exist in the geomagnetic data for the last 31 years; they may prove valuable in seeking to understand the solar wind–magnetosphere interactions. After the present study was completed another study was published [*Bell and Defouw*, 1964] in which similar conclusions were reached. Since the present method of analysis is quite different from that of Bell and Defouw, it is thought to be of interest to present it also.

Procedure. There are now available K_p indices for more than 31 years, consisting of more than 90,000 well-determined values of standard quality. They represent a detailed history (8 values per day) of the disturbance variations of the geomagnetic field over nearly three sunspot cycles. The scientific community is indebted to the late Professor J. Bartels and his collaborators for their dedicated efforts in the compilation of this series. The K_p index is a worldwide measure of geomagnetic activity expressed on a quasi-logarithmic scale and based on the measurements at a fixed group of 12 observatories in upper middle geomagnetic latitudes. The K_p index is traditionally taken to be a meassure of the velocity of the solar corpuscular stream. The Mariner 2 measurements of *Snyder et al.* [1963] establish with a considerable degree of certainty that the classical view is well taken.

Our search for a lunar influence on K_p began with the establishment of a suitable reference level with which to compare the magnetic activity at individual times during the lunar cycle. The mean value of K_p for each lunar synodic period was taken; this is called $\bar{K}_p$. The difference between each K_p value during the lunar month and $\bar{K}_p$ was found. This difference, divided by $\bar{K}_p$ and multiplied by 100, is the per cent departure of magnetic disturbance from the reference level.

$$\% \text{ departure} = 100(K_p - \bar{K}_p)/\bar{K}_p$$

Per cent departure was found for all the lunar synodic periods contained in the 31 years of K_p data. Mean values of the per cent departures (8 per day) that were taken during the course of the lunar cycle are shown in Figure 1. Figure 1 is the output of a plotter where each vertical marker represents one of the mean values of per cent departure. Figure 1 shows the following features: (*a*) A broad maximum of geomagnetic activity (≈4%) begins a half day after full moon and lasts nearly seven days. (*b*) A broad minimum of geomagnetic activity (≈4%) exists for about seven days preceding full moon. (*c*) There is nothing at new moon but random statistical fluctuations.

These results are generally unexpected, in view of the emphasis given to the new moon

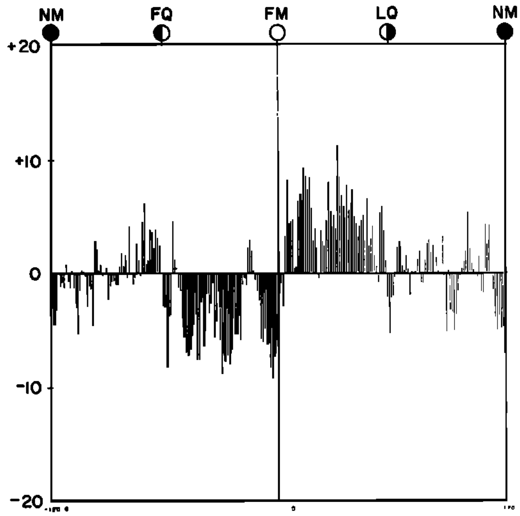

Fig. 1. Mean values of the per cent departures of K_p as a function of lunar phase (31 years of K_p data).

position by previous investigators, who have usually suggested some type of 'shadowing' mechanism at new moon.

Several additional studies were performed to examine the above conclusions.

1. To test the significance of the departures observed before and after full moon, and to determine if they might have originated in random fluctuations, a series of artificial lunar periods of 25, 26, 27, 28, 29, 30, 31, and 32 days were run through the same computer program using all the 31 years of K_p data in each case. In all these random data there were five cases when essentially clean departures of about 4% existed for periods of about three days, and three cases when departures of about 3% existed for periods of about four days. The normal departure lasts only about one day or less. As examples of the random data, Figures 2 and 3 are presented for the 27-day and 29-day runs, respectively. Figures 2 and 3 show more than one random negative departure comparable to the meaningless departure at new moon in Figure 1. Many more were found in the runs that have not been reproduced. There is nothing like the seven-day departures of Figure 1 in any of this set of random data.

2. It is not clear what statistical laws we should expect the frequency distribution of departures from the null axis to follow. Accord-

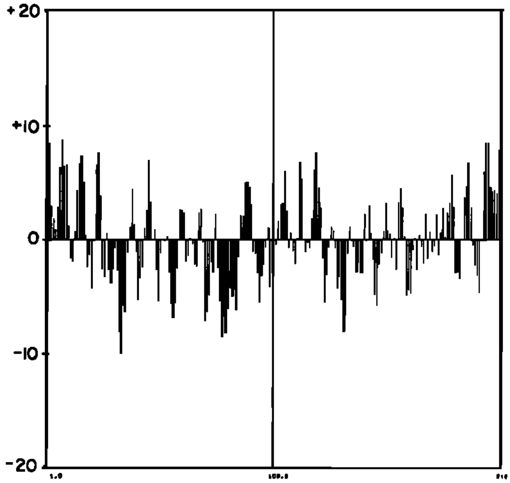

Fig. 2. Mean values of the per cent departure of K_p for 27-day periods (31 years of K_p data).

ingly, we have determined the distribution function empirically by a systematic randomization of the data used. This randomization was accomplished in the following manner. Each lunar month used here contains 241 three-hour intervals, 120 on each side of the three-hour interval during which full moon occurs. Each point of Figure 1 is an average performed separately for each three-hour interval in the superposition of lunar months. Therefore 120 fictitious superpositions of the lunar months were made by shifting the positions of the three-hour intervals of each lunar month, those pieces of data shifted off one end of the month being shifted in on the other end. In general, in the mth superposition the data of the nth lunar month were shifted $2mn$ positions. In this way 120 randomized diagrams equivalent to Figure 1 were obtained. Two studies were made of the properties of these diagrams.

Let us define an excursion length as the number of three-hour intervals adjacent to one another in which the departure from zero has the same sign (positive or negative). The number distribution of the excursion lengths was found by summing all those in the 120 randomized cases and dividing by 120; this distribution is shown by the histogram in Figure 4. Also plotted in Figure 4 is the actual distribution of excursion lengths in Figure 1 (denoted by crosses). The probability that a single case will contain an excursion length equal to or greater than some value can be determined by summing the histogram upward from the point under consideration. Figure 1 contains two large excursion lengths. If the probabilities of their occurrence in the same case can be considered independent, then the probability of their occurring by chance turns out to be 0.035.

Let us define an excursion area as an excursion length multiplied by the average per cent departure during the excursion. The distribution of excursion areas was calculated in the same way as described above for excursion lengths; the results are shown in Figure 5. Once again the crosses represent the data of Figure 1. If the two high points of the Figure 1 data have independent probabilities of occurrence, then the probability that a case like Figure 1 would arise by chance is 0.0074. Since it is possible that the presence of one large excursion area might slightly enhance the probability of occurrence of somewhat larger excursion areas associated with the excursions of the opposite sign, it is possible that the above value may slightly underestimate the true probability of occurrence of two large excursion areas in a single case.

In any event it seems safe to state that the probability of occurrence of Figure 1 by chance is less than 5%, the level of probability below which a distribution is usually considered to have statistical significance.

3. To examine further the effects observed before and after full moon, two separate runs

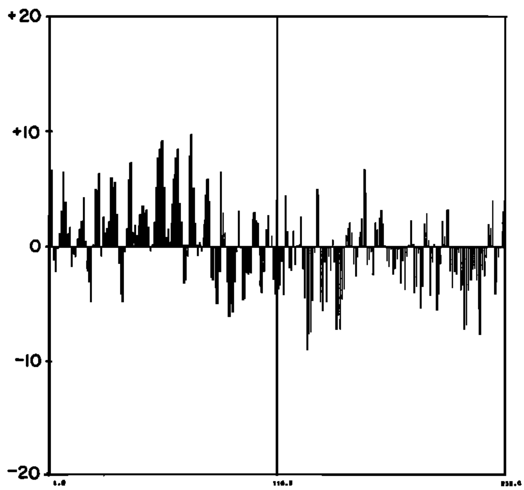

Fig. 3. Mean values of the per cent departure of K_p for 29-day periods (31 years of K_p data).

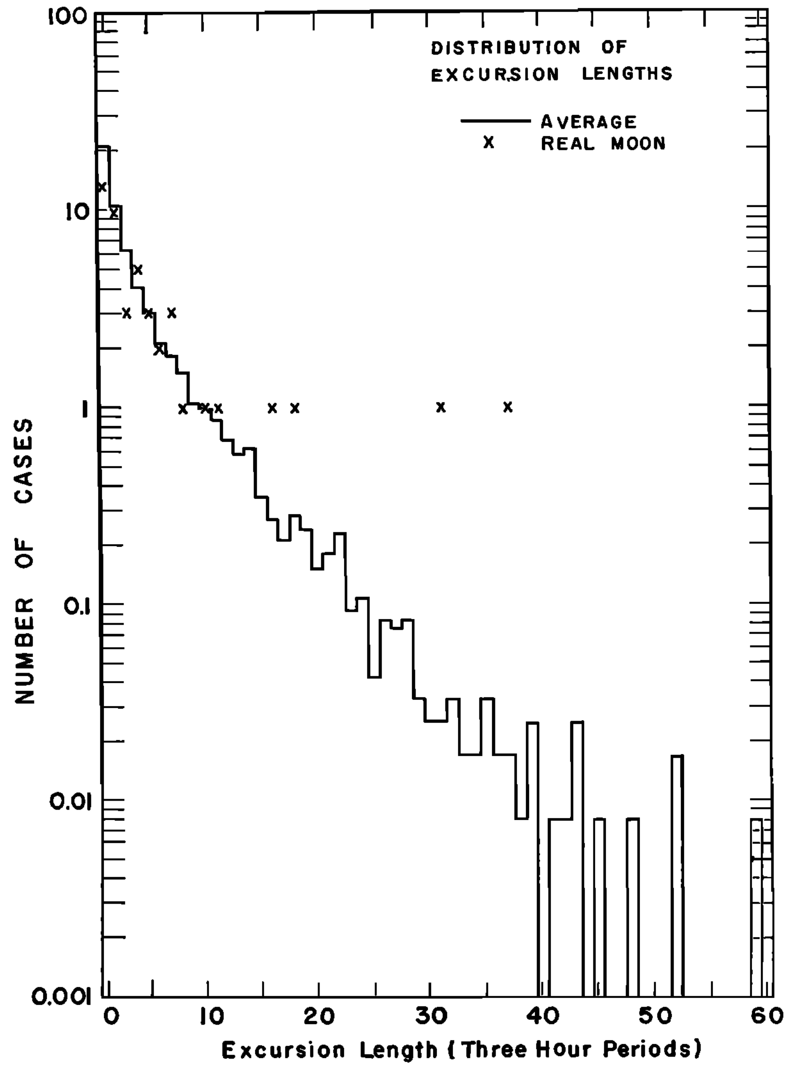

Fig. 4. Frequency distribution of excursion lengths calculated from the 120 averages of randomized lunar periods, compared to the distribution found for Figure 1.

of per cent departures were made, each for eight years of data only. The first was for the eight years of the quiet sun consisting of K_p indices from 1932, 1933, 1934, 1942 (last half only), 1943, 1944, 1953, 1954, and 1955 (first half only). The second was for the eight years of the disturbed sun consisting of K_p indices from 1937, 1938, 1939 (first half only), 1947, 1948, 1949, 1957, 1958, and 1959 (first half only). Figures 6 and 7 represent the results of this study. For the quiet sun (Figure 6), when fluctuations of K_p are expected to be small, the previously observed effects occur as found in Figure 1. For the disturbed sun (Figure 7), when random fluctuations of K_p are expected to be large, the effects about full moon exhibit a considerably more randomized pattern.

4. Instead of using the Zurich relative sunspot numbers to distinguish those periods of strong solar plasma flow from the quieter periods, the $\bar{K}_p$ values themselves might be used. In this study the 382 lunar periods were divided into four groups on the basis of different levels of $\bar{K}_p$. All four groups were run through the same

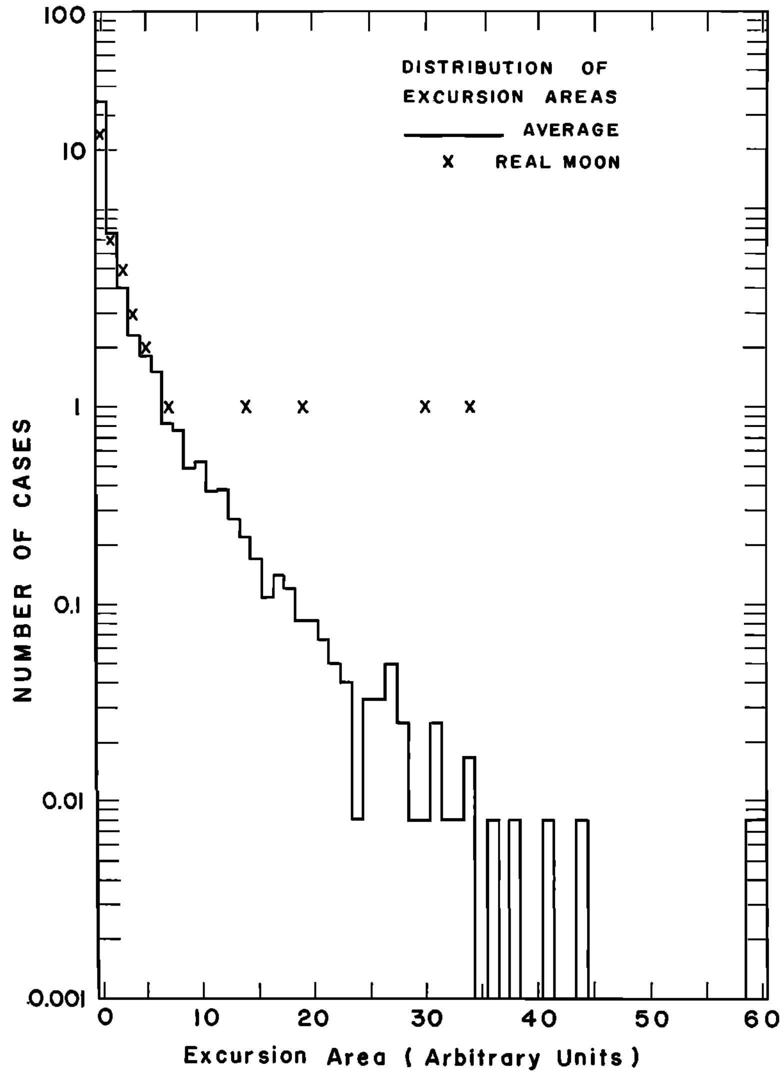

Fig. 5. Frequency distribution of excursion areas calculated from the 120 averages of randomized lunar periods, compared to the distribution found for Figure 1.

per cent departure analysis. The results for the lowest to the highest $\bar{K}_p$ groups are shown in Figures 8, 9, 10, and 11, respectively. In Figure 8 the random fluctuations of K_p are expected to be small, and the observed lunar effects of Figure 1 are seen to be present. In Figure 11 the random fluctuations of K_p are expected to be large, and the effects at full moon are not evident. The figures for the two intermediate groups represent a gradation between Figures 8 and 11. The lunar periods assembled to form Figure 8 are not necessarily those of Figure 6, nor are those of Figure 11 the same as the lunar periods of Figure 7. In fact, they are not the same in more than half the cases. This is not surprising when we remember the occurrence of disturbed periods in low sunspot years or quiet periods in high sunspot years.

Bartels [1964] has previously reached the conclusion that there is no evidence for a lunar effect on geomagnetic activity during disturbed periods. His analysis was based upon the daily K_p sums of 30 or greater during 1932–1961 and on magnetic character figures C_i of 1.3 or higher

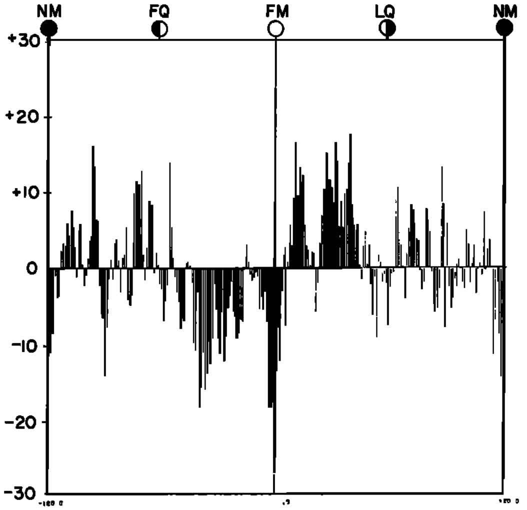

Fig. 6. Mean values of the per cent departure of K_p as a function of lunar phase (8 quiet sun years only).

for 1884–1961. Our analysis presented above is fully in agreement with his conclusion.

Discussion. It has been shown that for the last 31 years geomagnetic activity has been on the average ≈4% smaller for the period beginning after lunar first quarter and lasting until just after full moon and that it has been on the average ≈4% greater from just after full moon until last quarter.

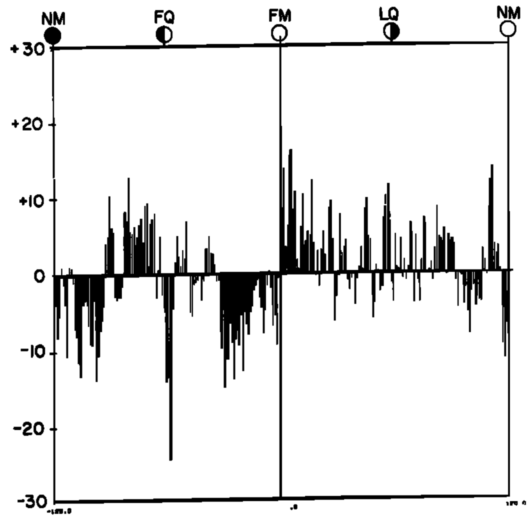

Fig. 7. Mean values of the per cent departure of K_p as a function of lunar phase (8 disturbed sun years only).

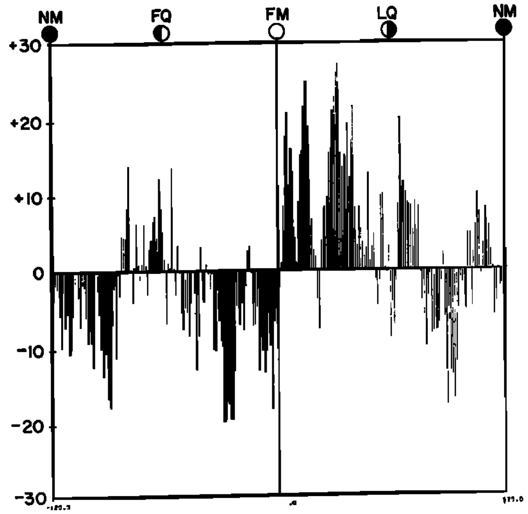

Fig. 8. Mean values of the per cent departures of K_p as a function of lunar phase ($\bar{K}_p$ values of the lowest quarter only).

Similar perturbations of the general level of of the K_p index have been found in an analysis by *Michel et al.* [1964]. These authors note that magnetic perturbations persist for about three days, and hence they do not consider their longer effects near full moon as more than statistical fluctuations.

Another technique that can be applied to this problem is that of autocorrelation analysis, to

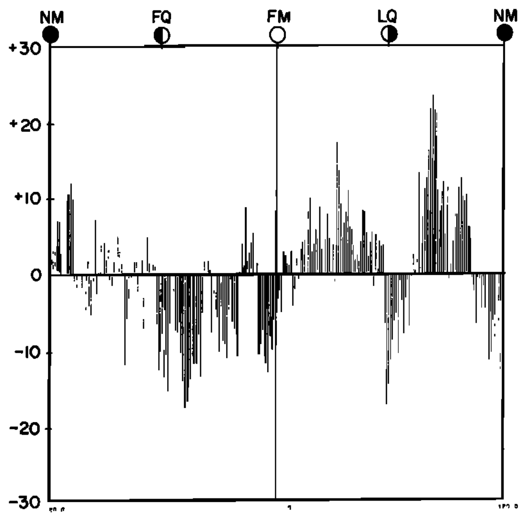

Fig. 9. Same as Figure 6 ($\bar{K}_p$ values of the next to the lowest quarter only).

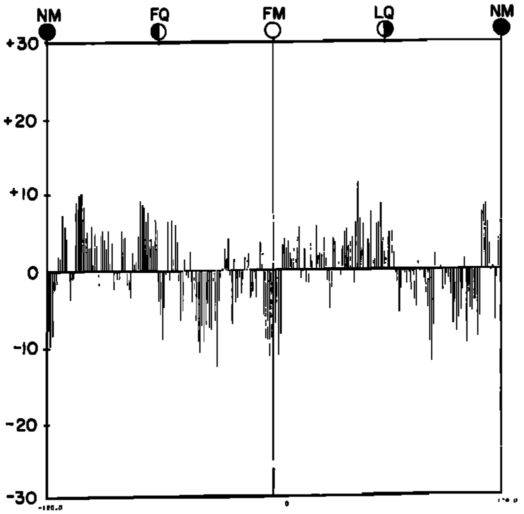

Fig. 10. Same as Figure 6 ($\bar{K}_p$ values of the next to the highest quarter only).

determine whether there is any regularity to the K_p pattern associated with a lunar month of 29.5 days. It is well known that such effects are associated with the 27-day period of rotation of the sun. We appreciate very much receiving permission to report that Shapiro and Ward (private communication, 1964) have applied the technique of 'power spectrum' analysis to compute a single spectrum from 80 years of C_i data. In a general region of enhanced power centered on a frequency corresponding to the solar rotation period, this spectrum shows two peaks, the principal one near 27 days, and another peak, somewhat smaller, near 29.5 days. They have sufficient resolution in the spectrum between 27 and 29 days to determine that two distinct peaks are present. Shapiro and Ward consider the physical reality of the peak at 29.5 days to be uncertain at this time.

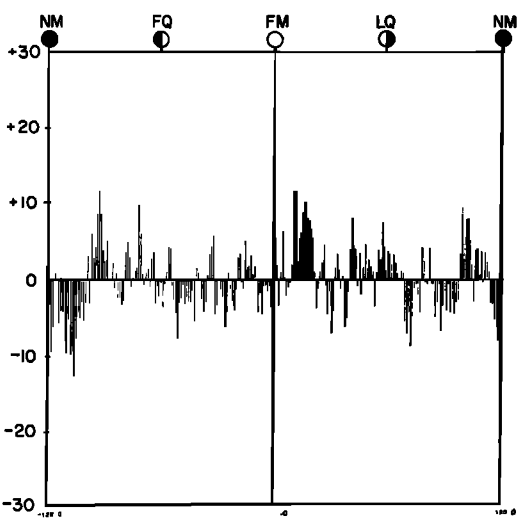

Fig. 11. Same as Figure 6 ($\bar{K}_p$ values of the highest quarter only).

Any physical mechanism to account for the variations of geomagnetic activity about full moon must be sought in the interactions between the moon and the tail of the geomagnetic cavity formed by the magnetosphere embedded in the flow of the solar wind.

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